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**APPLICATION OF IRIS/IDA STATIONS IN THE
USSR TO SEISMIC MONITORING RESEARCH:**

**The Use of Velocity Spectrum in the Stacking of
Receiver Functions with Application to IRIS
Station at Obninsk, USSR**

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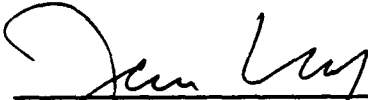
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The Use of Velocity Spectrum in the Stacking of Receiver Functions with Application to IRIS Station at Obninsk, USSR

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SUMMARY

In order to improve the signal to noise ratio of receiver function data, it is typical to stack receiver functions calculated from events at similar distances and back azimuths. We have adapted the velocity spectrum stacking technique, used extensively in reflection seismology, to the receiver function method in order to stack data with different ray parameters, thereby improving further the signal to noise ratio. Perhaps more importantly, by producing the velocity spectrum stacks we take advantage of the differences in the shapes of the moveout curves of converted phases and reverberations to identify and separate the various phases and to infer velocity structure. Through conventional receiver function techniques we have modeled the crustal structure beneath the Soviet IRIS seismographic station at Obninsk. This model includes a low velocity 2 km thick surface layer and 47 km depth to Moho with relatively uncomplicated crustal structure. By comparison of velocity spectrum stacks produced from the observed data at Obninsk with those produced from PREM synthetics we have identified Ps phases from the 410 and 670 km discontinuities. We find no evidence of a 210 km discontinuity beneath Obninsk in the receiver function data.

Key words: receiver function, Obninsk, velocity spectrum stack, normal moveout, upper mantle discontinuity.

INTRODUCTION

A commonly used technique to estimate crust and upper mantle structure from a single three-component seismographic station is to compute and interpret "receiver functions" (e.g., Langston 1989, 1981, 1979, 1977; Owens, Crosson and Hendrickson 1988; Owens and Crosson 1988; Owens, Taylor and Zandt 1987; Owens, Zandt and Taylor 1984), wherein the horizontal components are deconvolved by the vertical component to produce a trace consisting primarily of

Ps conversions and converted S-wave reverberations. The technique has been successfully extended to arrays of broadband portable stations by Owens et al. (1988a,b). To improve the signal to noise ratio, receiver functions can be binned by ray parameter and back azimuth and stacked (Owens, Taylor and Zandt 1983; Owens 1984). In areas with flat geological structure the receiver functions show little or no azimuthal dependence and can be stacked at common ray parameter for all azimuths. However, if we wish to stack traces with different ray parameters, we must first correct for the differences in relative arrival times.

The "velocity spectrum stack" (VSS) is a useful tool for stacking reflection data within a range of ray parameters in multichannel studies (e.g. Yilmaz 1987). The functional dependence of arrival times on ray parameter p , relative to a reference phase with ray parameter p_0 is called the "moveout". The "normal moveout correction" (NMO) then refers to the time adjustment necessary to correct the arrival time to what would have been observed from a vertically incident ray, irrespective of amplitude, assuming a given velocity structure. The "velocity spectrum stack" is a contour map of amplitudes across constant velocity stacks (produced by stacking the observed records after NMO assuming a uniform velocity) in the velocity-time plane (e.g. Sheriff 1982). A phase present in the receiver functions is thus enhanced if the appropriate NMO correction is made. The enhancement will be most effective for a value of velocity matching the "true" mean velocity sampled by the phase. It is most appropriate at this point to think of the velocity structure as a function of time since arrival time is observed whereas depth will be computed after the velocity structure is determined (Yilmaz 1987). Because of differences in the shapes of their moveout curves, separate stacks must be produced for each of the prominent phases present in the receiver functions. Therefore, the velocity spectrum stacks can be used to distinguish between phases as well as to infer velocity structure.

The examples in the following sections, describing the production of VSS, use radial components of the receiver functions. Since the production of the VSS depends only on travel time, the tangential component VSS can be produced using the same procedure, however for 1-dimensional structure there will be no energy on the tangential components.

METHOD

Figure 1 illustrates the geometry of the most significant type of phase observed in receiver function studies - the P to S conversion (Ps) generated when the wave crosses an interface - for a layer over a half space. The time delay for the Ps arrival relative to that of the P arrival $\Delta T_{Ps}(p)$ is given by:

$$\Delta T_{Ps}(p) = T_S + T_h - T_P \quad (1)$$

$$\Delta T_{Ps}(p) = z \left(\sqrt{V_S^2 - p^2} - \sqrt{V_P^2 - p^2} \right) \quad (2)$$

In the above equations: T_S , T_h and T_P are travel times along the paths labeled in Figure 1; V_S and V_P are the average S and P velocities in the layer, respectively; p is the ray parameter; and z is the depth to the interface. In terms of the vertical travel time of Ps relative to P (ΔT_{Ps0}) through the layer and the velocity ratio $r = V_P / V_S$, we have:

$$\Delta T_{Ps}(\Delta T_{Ps0}, p, V_S, r) = \frac{r \Delta T_{Ps0}}{r - 1} \left(\sqrt{1 - p^2 V_S^2} - \sqrt{r^2 - p^2 V_S^2} \right) \quad (3)$$

Note that this equation depends only on ΔT_{Ps0} , p , V_S and an assumed value for r (which will be held constant for an entire velocity spectrum stack, e.g. $r = \sqrt{3}$ for a Poisson solid). Figure 2 depicts a set of synthetic receiver functions generated for a layer ($V_P = 6.0$ km/sec, $V_S = 3.5$ km/sec) over a half space ($V_P = 8.0$ km/sec, $V_S = 4.6$ km/sec, and $z = 40$ km) for a range of ray parameters. We see that the Ps phase is delayed with increasing ray parameter relative to the initial P-wave, illustrating the Ps moveout. All phases (reverberations) following Ps are advanced in arrival time relative to the P phase with increasing ray parameter. The next prominent phase after the Ps arrival is composed of the sum of all reverberations in which there are two P legs and one S leg. Figure 3 depicts the travel path of the Ppps phase in which the first two branches are P waves and the final branch is an S. For near vertical incidence the reverberations ending in an S branch will contribute much more energy to the horizontal components than those ending in a P (ie. Pssp, and Ppsp). For convenience of notation we will adopt a naming convention for the sum of these reverberations as Pnpms, in which n is the number of p legs and m is the number of s legs (if n or m is zero it is omitted). The phase described will be referred to as P2p1s. The next phase on Figure 2, P1p2s, composed of the sum of reverberations with two S legs and one P, has two contributions with final S legs (the PspS and Ppss) and a less significant Pssp contribution.

We take advantage of this difference in the shape of the moveout curve to distinguish reverberations from the Ps phase. Equation 4 gives the time delay (ΔT_{P2p1s}) for the P2p1s phase relative to the P arrival for a layer over a half space:

$$\Delta T_{PPS}(\Delta T_{PPS0}, p, V_S, r) = \frac{r \Delta T_{PPS0}}{r + 1} \left(\sqrt{1 - p^2 V_S^2} + \sqrt{r^2 - p^2 V_S^2} \right) \quad (4)$$

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In like fashion, we can derive moveout equations for the P3p, P1p2s and P3s phases. However P3p and P3s have small amplitudes (even after stacking a very large number of events) so are usually of little significance in interpretations. P1p2s, on the other hand, has reversed polarity and is easily distinguishable from Ps and P2p1s, so it is sometimes a useful phase in the interpretation of receiver structure.

Constant velocity stacks are produced by averaging along the moveout curve the amplitudes of N receiver functions with various ray parameters.

$$S(\Delta T_{\Phi 0}, V_s) = \frac{1}{N} \sum_{i=1}^N f_i\{\Delta T_{\Phi}(\Delta T_{\Phi 0}, p_i, V_s, r)\} \quad (5)$$

Where Φ is the type of phase (ie. Ps or P2p1s); $S(\Delta T_{\Phi 0}, V_s)$ is the averaged amplitude at a given zero offset time and S-wave velocity; $f_i\{\Delta T_{\Phi}(\Delta T_{\Phi 0}, p_i, V_s, r)\}$ is the amplitude of the i^{th} trace at the computed moveout time, $\Delta T_{\Phi}(\Delta T_{\Phi 0}, p_i, V_s, r)$, for a given wave type (Φ). If the moveout time falls between two samples we linearly interpolate a value for $f_i\{\Delta T_{\Phi}(\Delta T_{\Phi 0}, p_i, V_s, r)\}$. After producing constant velocity stacks for the range of all reasonable velocities, we contour the amplitudes in the velocity-time plane to produce the "velocity spectrum stack" (VSS). The Ps conversion or P2p1s reverberation on their respective velocity spectrum stacks will appear as positive ridges (negative for a velocity inversion) elongated parallel to the velocity axis. The velocity structure beneath a station can then be inferred by selecting the time and velocity of the highest amplitude on each ridge.

A SYNTHETIC EXAMPLE

Figure 4 depicts VSS produced for the Ps and P2p1s phases for the synthetic receiver functions shown in Figure 2. Upon inspection of the Ps stack (left) we observe good time resolution for Ps near 5 seconds but poor velocity resolution. This phase also appears on the P2p1s stack (right), but the peak is not as sharp and does not have as large an amplitude as on the Ps stack. P2p1s (at 18 sec) is only observed on the P2p1s stack and has much better velocity resolution than Ps. It is not surprising that we are able to pick $V_S=3.5$ km/sec (the velocity used to compute the synthetics in Figure 2) more accurately from P2p1s stack, since Figure 2 shows twice as much moveout for P2p1s than for Ps. We can use this velocity together with the approximate 4.8 sec arrival time on the Ps stack to compute the thickness of the layer. The arrival times on the VSS are zero offset arrival times, so equation (2) becomes:

$$T_{Ps} = z \{1/V_S - 1/V_P\} \quad (6)$$

Solving for z we find a 40 km depth to Moho.

Figure 5 depicts single stacks of the receiver functions shown in Figure 2. The top stack has no moveout applied - the next three are stacked using the respective P_s , $P2p1s$, and $P1p2s$ moveout curves (from top to bottom). In each case the respective velocity depth (time) function was picked by observation of the stacking amplitudes on the corresponding VSS (Figure 4). The P , P_s , $P2p1s$, and $P1p2s$ arrivals are at 5, 10, 23 and 28 seconds respectively. Figure 5 clearly illustrates the fact that the various arrivals are substantially enhanced when stacked under the appropriate moveout curve. An added bonus is the annihilation of the reverberations ($P2p1s$ and $P1p2s$) on the P_s stack and conversely the P_s phase is greatly diminished on the two reverberation stacks. We conclude that by producing the stacks with normal moveout we may observe arrivals that would otherwise be below noise levels and avoid mislabeling other phases.

Figures 6 and 7 depict the shape of the P_s and $P2p1s$ moveout curves computed for various depths using the PREM velocity model (Dziewonski and Anderson, 1981) over the range of ray parameters typical of P-arrivals used in receiver function studies (0.04 to 0.08 sec/km or an arc distance of 30° to 90°). For an interface depth of 50 km, there is 0.75 sec. of moveout over this range of ray parameters. There is about 2.5 sec. of moveout calculated over the same range of ray parameter for the $P2p1s$ phase at the 50 km depth. We observed in Figure 4 that for an even shallower depth (40 km.), with less moveout, reasonable signals appeared on the VSS for both phases. For the P_s phase, there are 1.8 sec. of moveout at 100 km and at 600 km there are 16.1 sec. of moveout over the range of ray parameters. It is clear that with a finite number of traces to stack VSS produced for the P_s phase will be much more useful in the interpretation of upper mantle structure than for crustal structure.

On the other hand, about 1.25 seconds of moveout is expected for the $P2p1s$ over the given range of ray parameter at the 25 km depth. Because of the greater amount of moveout observed for this phase their VSS may prove to be more valuable in the interpretation of shallow structure. The longer ray path of the reverberations (as opposed to the direct P_s) make this phase more sensitive to heterogeneities in the near surface structure. As a result interpretation of these phases may be more difficult (Owens et al. 1984).

It is clear from Figure 6 that to produce reliable VSS for shallow layers (100 km or less), data from the full range of ray parameters are necessary. For the P_s phases from deeper interfaces and

the P2p1s phase at all depths, it appears that there is sufficient moveout along the curves to produce VSS from data with sparser distribution data than for the shallower layers. In cases where there is not enough distribution to use VSS to make a preliminary estimate of V_s , it may be desirable to restack the data after making a moveout correction (not necessarily normal moveout) using a regional velocity model in order to stack the data more coherently.

CRUSTAL STRUCTURE AT OBN

We calculated Velocity Spectrum Stacks for data recorded at the Soviet station at Obninsk (OBN). We use conventional receiver response interpretation to determine crustal structure and use the VSS method in the following section to look at upper mantle discontinuities.

We have computed receiver functions for the IRIS/IDA station at OBN using data collected in 1989-90 (Gurrola, Minster and Owens 1990a,b). The station is equipped with a broadband three-component system with response nominally flat with respect to velocity from approximately 3 mHz to 5 Hz. We used teleseismic P and PP phases which, due to the uneven distribution of source regions during the one year period covered by the data, primarily sample the northeast and southeast quadrants at all sites. It was necessary to high-pass filter most of these data in order to counter the effects of occasional nonlinear noise problems at frequencies lower than 20 mHz.

The broad band OBN receiver functions are dominated by reverberations in a shallow surface layer. In order to identify phases from deeper layers, we have reduced the contribution of the near surface layer by low-pass filtering these data with a phaseless Gaussian filter (centered at 0 Hz with a half power width of 0.6 Hz, Figure 8). The velocity structure was determined using the smooth inversion of Ammon (personal comm., 1990), which employs the reflection matrix method (Kennett, 1983, and Randall, 1989). The simplest model that we could construct which satisfies both the broad band and the high frequency data includes a low velocity surface layer of no more than 2.5 km thickness and a rather smoothly increasing velocity gradient to the 47 km deep Moho (Gurrola et al. 1990a, Figure 9).

UPPER MANTLE DISCONTINUITIES AT THE OBN IRIS/IDA STATION

VSS produced from OBN receiver functions exhibit clear arrivals from the upper mantle discontinuities. The top row of Figure 10 depicts the Ps VSS computed from synthetics produced for the PREM velocity structure modified to include the OBN crustal structure (left) and the Ps stacks computed from the observed data at OBN (right). The PREM model used to compute these synthetics was modified to include the OBN velocity structure described above. The bottom row depicts the corresponding P2p1s stacks. We observe Ps and P2p1s phases from the Moho at about 5 and 20 seconds respectively. The contour interval was chosen to illustrate best the upper mantle arrivals not observable on the individual receiver functions. As a result, the Moho arrivals are not very sharp in these plots. We chose to use a uniform Poisson ratio in computing the VSS. Had we allowed the V_p -to- V_s ratio vary with depth as given in the PREM model, all arrivals would appear slightly sooner in time and lower in velocity. The effect of this approximation will be the same on VSS computed for synthetics as for those computed for observed data and varying this ratio with depth would add another free parameter and unnecessarily complicate the interpretation.

The observed Ps phase from the 410 km discontinuity (at 42 seconds on the velocity spectrum stacks of Figure 10) exhibits much higher amplitude than the PREM synthetics. This is consistent with the larger velocity contrast for the 410 km discontinuity suggested by the K8 model of Given and Helmberger (1980). The Ps arrival from the 670 km discontinuity is similar in amplitude on both the observed stacks and the PREM synthetics, which implies a similar velocity contrast, although this arrival appears slightly earlier and at a higher velocity in the observations. The time delay between the 410 and 670 km discontinuities is smaller than observed in PREM, which is consistent with independent observations at OBN by Vinnik (personal comm., 1990).

We do not observe a 210 km discontinuity beneath OBN. The Ps phase from the 210 km discontinuity arrives just after the P2p1s from the Moho for the PREM model making the peak at 20 seconds on the synthetic velocity spectrum stacks broader than observed. The strong P2p1s arrival from the 210 km discontinuity observed at 75 seconds on the PREM VSS is not apparent in observed VSS (Figure 10). These observations lead us to conclude that there is no 210 km discontinuity beneath OBN, or at least that it is not as pronounced as in PREM.

CONCLUSIONS

Through the use of velocity spectrum stacks we can to stack data from different ray parameters, and by doing so infer velocity structure beneath the seismographic station. Velocity spectrum stacks analysis can be used to distinguish between a Ps phase and a P2p1s reverberation based on the difference in the shape of their respective moveout curves. The method looks most promising for the interpretation of upper mantle structure, however when the full range of ray parameter are available crustal phases may also be imaged with VSS.

Through the analysis of velocity spectrum stacks produced for data from OBN, we have been able to identify upper mantle Ps conversions associated with the 410 and 670 km discontinuities that were not observable in the individual receiver functions. We have also given evidence that the 210 km discontinuity is not present beneath O3N.

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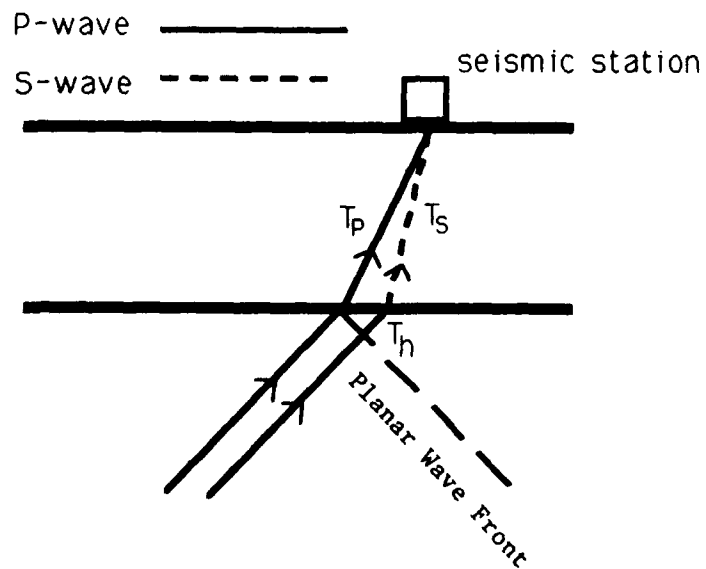


Figure 1. Ray paths for the Ps phase relative to the P phase for a layer over a half space. T_p and T_s are the travel times of the P and S phases with the same ray parameter through the layer respectively. T_h is the travel time differential in the half space for the two rays assuming a planar wave front.

Synthetic Receiver Functions

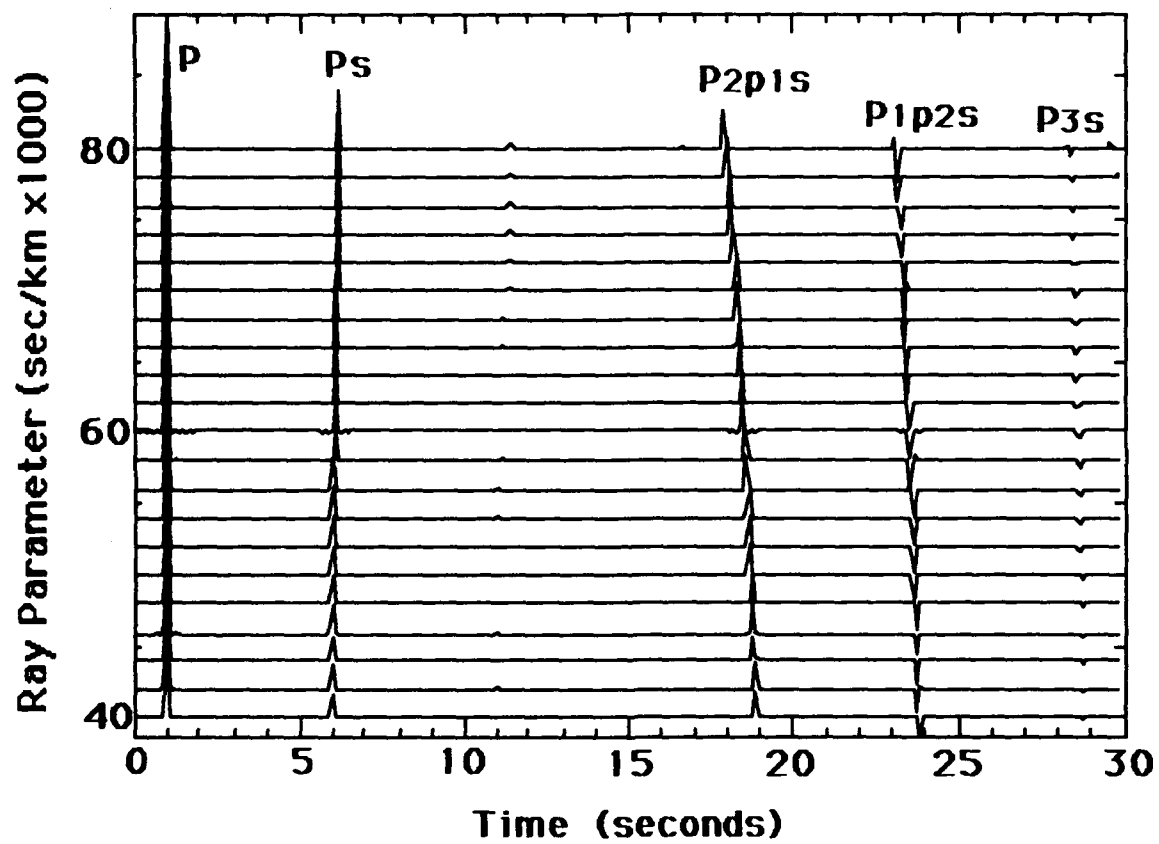


Figure 2. Seismic section of synthetic receiver functions computed for a layer ($V_p=6.0$ km/sec, $V_s=3.5$ km/sec) over a half space ($V_p=8.0$ km/sec, $V_s=4.6$ km/sec).

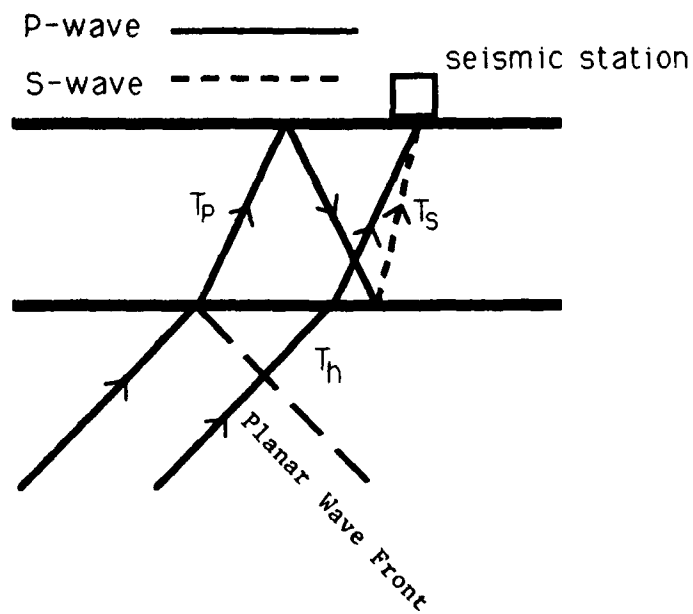


Figure 3. Ray paths for the P_2p_1s phase relative to the P phase for a layer over a half space. T_P and T_S are the travel times of the P and S phases with same ray parameter through the layer respectively. T_h is the travel time differential in the half space for the two rays assuming a planar wave front.

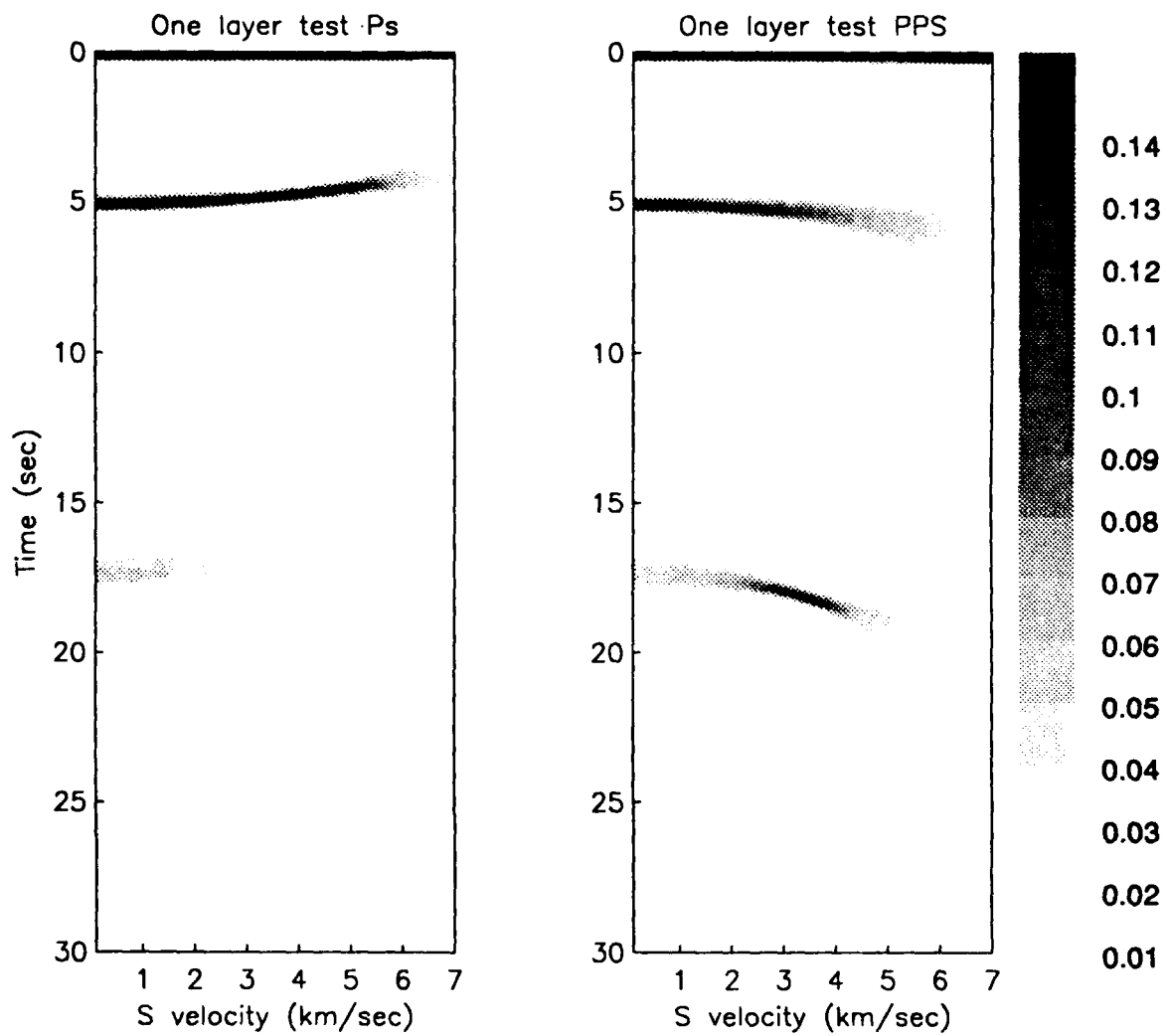


Figure 4. Velocity spectrum stacks produces from the synthetic receiver functions depicted in Figure 2. Ps stacks are shown on the left and P2p1s stacks are on the right.

Stacked Synthetic Receiver Functions

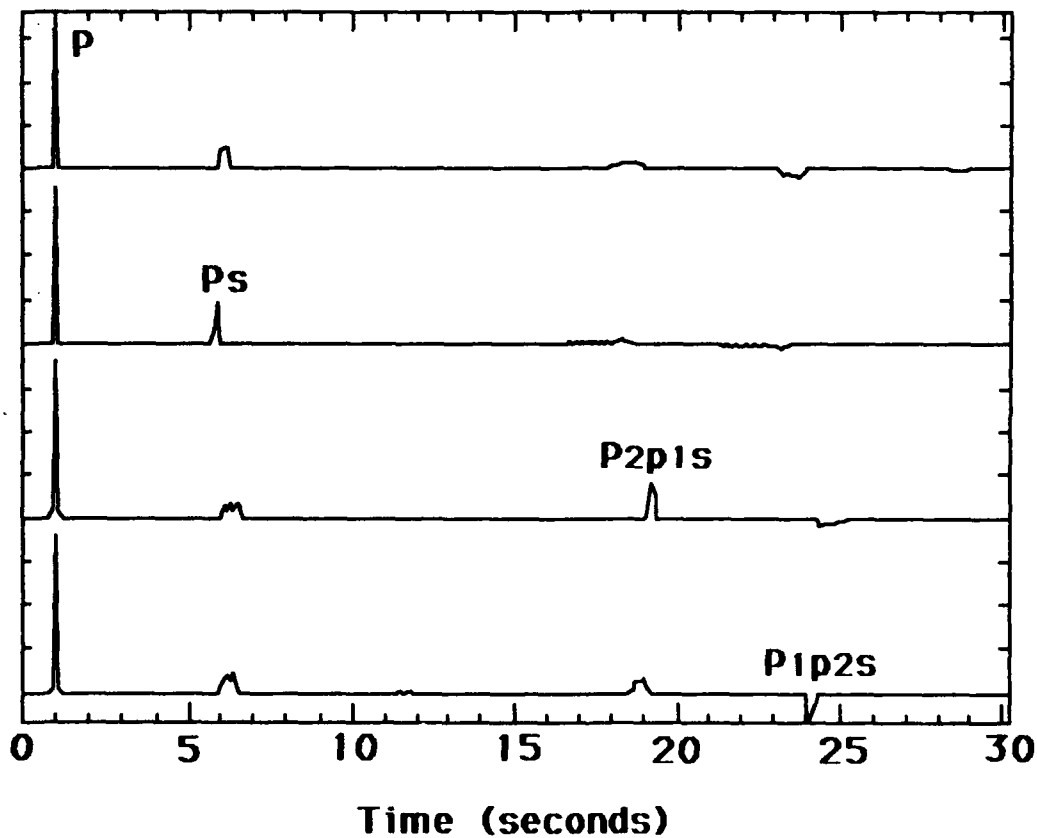


Figure 5. Stacks of the synthetic receiver functions depicted in Figure 2. On top is a straight stack with no time correction applied. The bottom three receiver function stacks are computed after applying the appropriate normal moveout correction for Ps, P2p1s, and P1p2s respectively (from top to bottom).

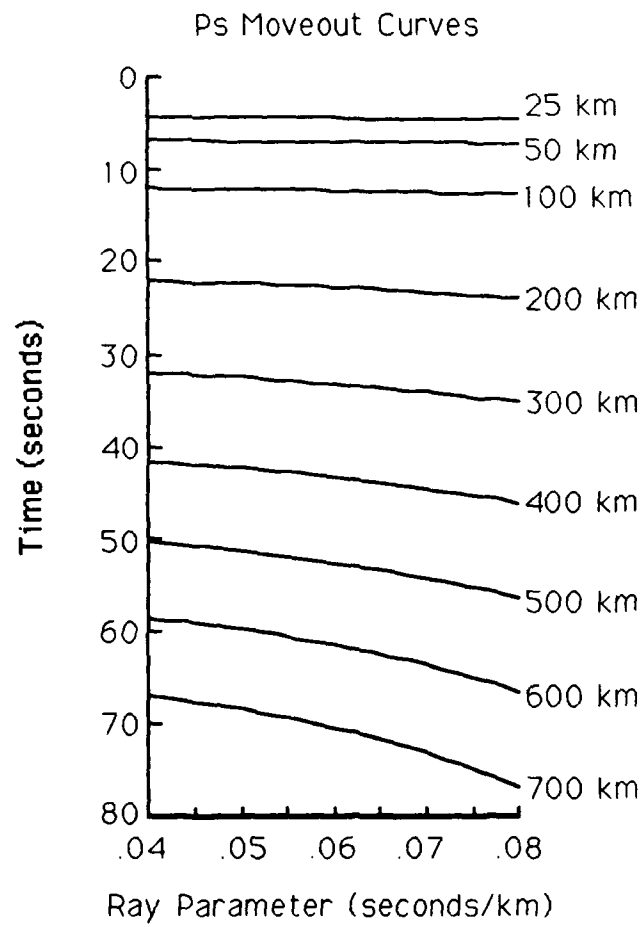


Figure 6. Moveout curves at various depths from 25 km to 700 km for the Ps phase computed for the PREM velocity structure. The depths associated with each curve are printed on the left.

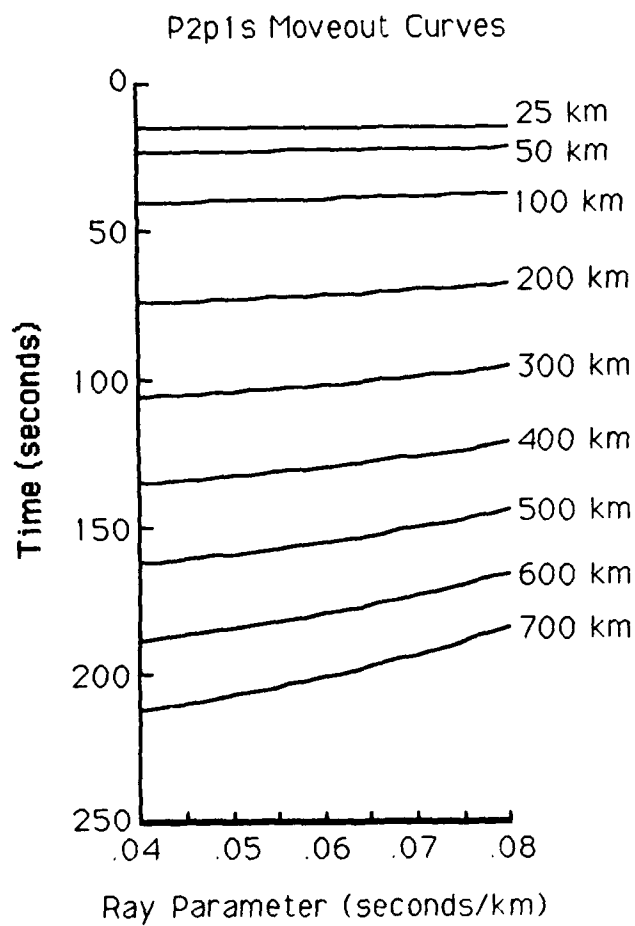


Figure 7. Moveout curves at various depths from 25 km to 700 km for the P2p1s phase computed for the PREM velocity structure. The depths associated with each curve are printed on the left.

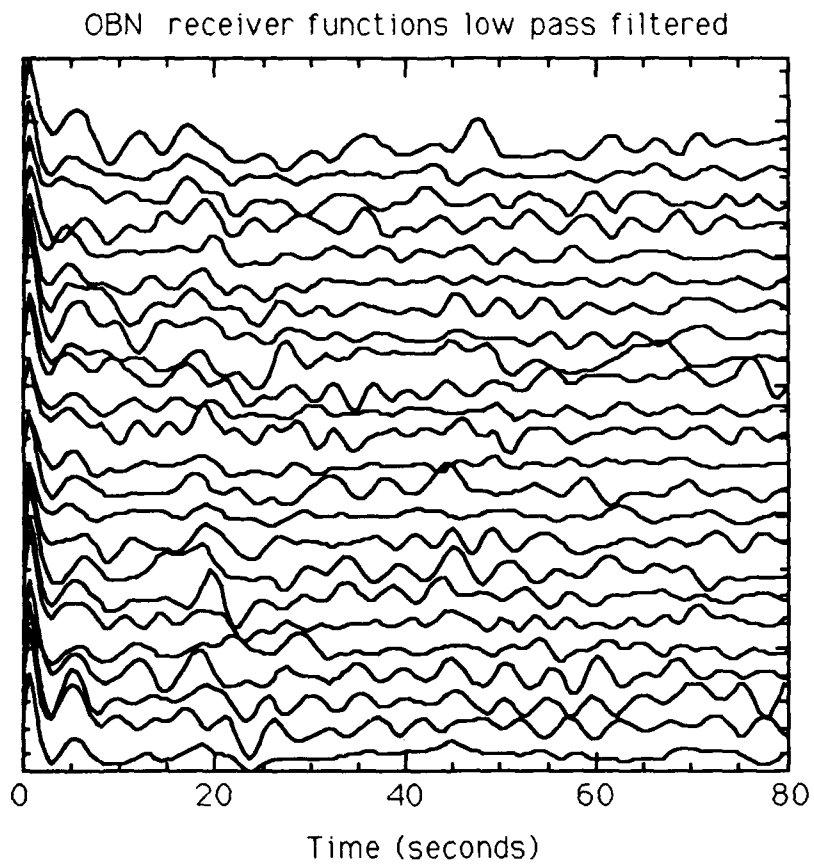


Figure 8. Low pass filtered individual receiver functions computed for OBN. The only clear arrivals without stacking are the Ps conversion from the Moho at 5 seconds and, in a few receiver functions the P2p1s and P1p2s from the Moho at 20 and 23 seconds respectively.

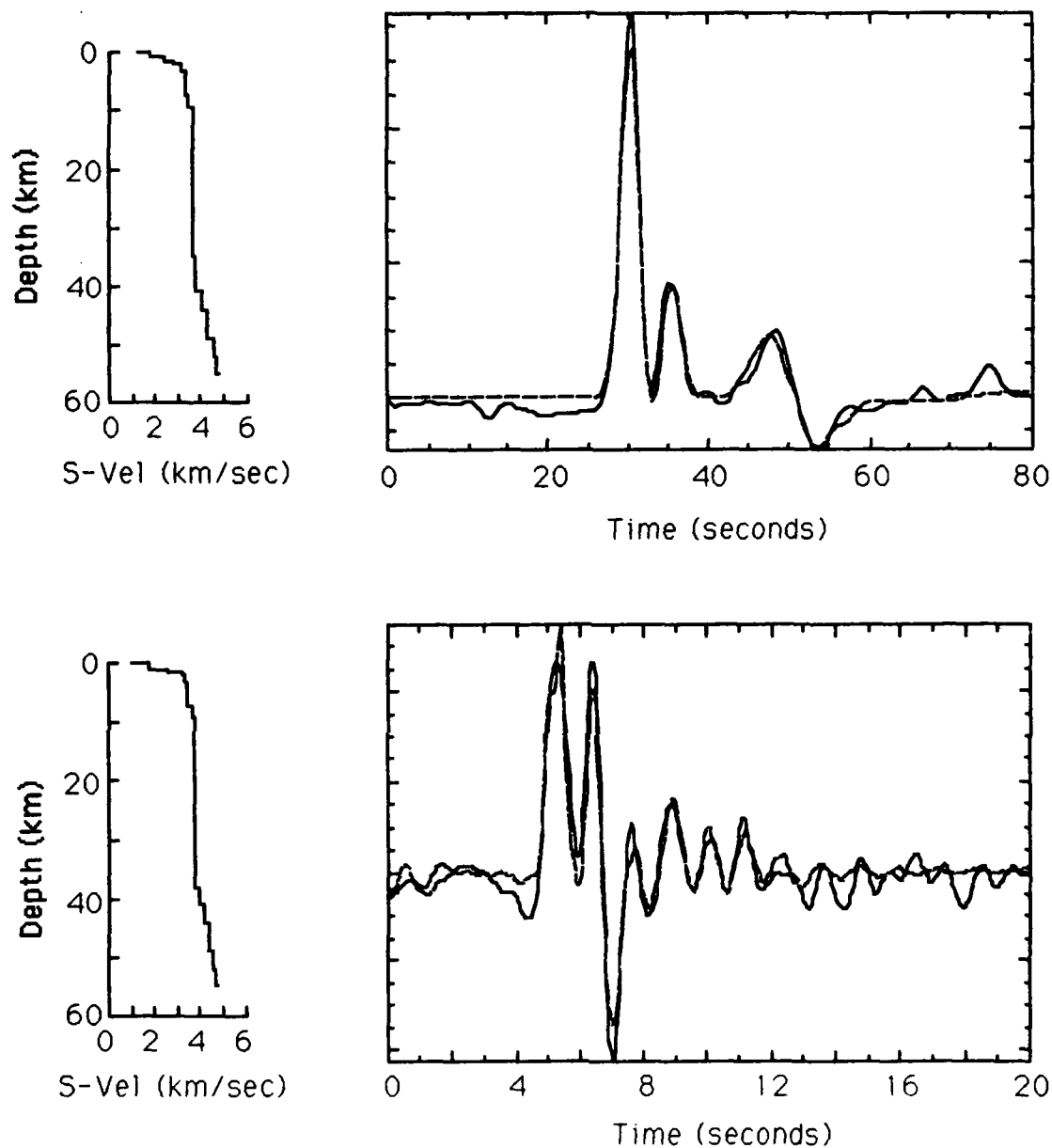


Figure 9. The synthetic (solid line) and observed (dashed line) stacked receiver functions computed for the Soviet Seismographic station at Obninsk. The synthetics pertain to the crustal structure models depicted to the left of the respective receiver functions. The low pass filtered response (stack of the receiver functions given in figure 8) is given on the top figure; the broad band results are on the bottom.

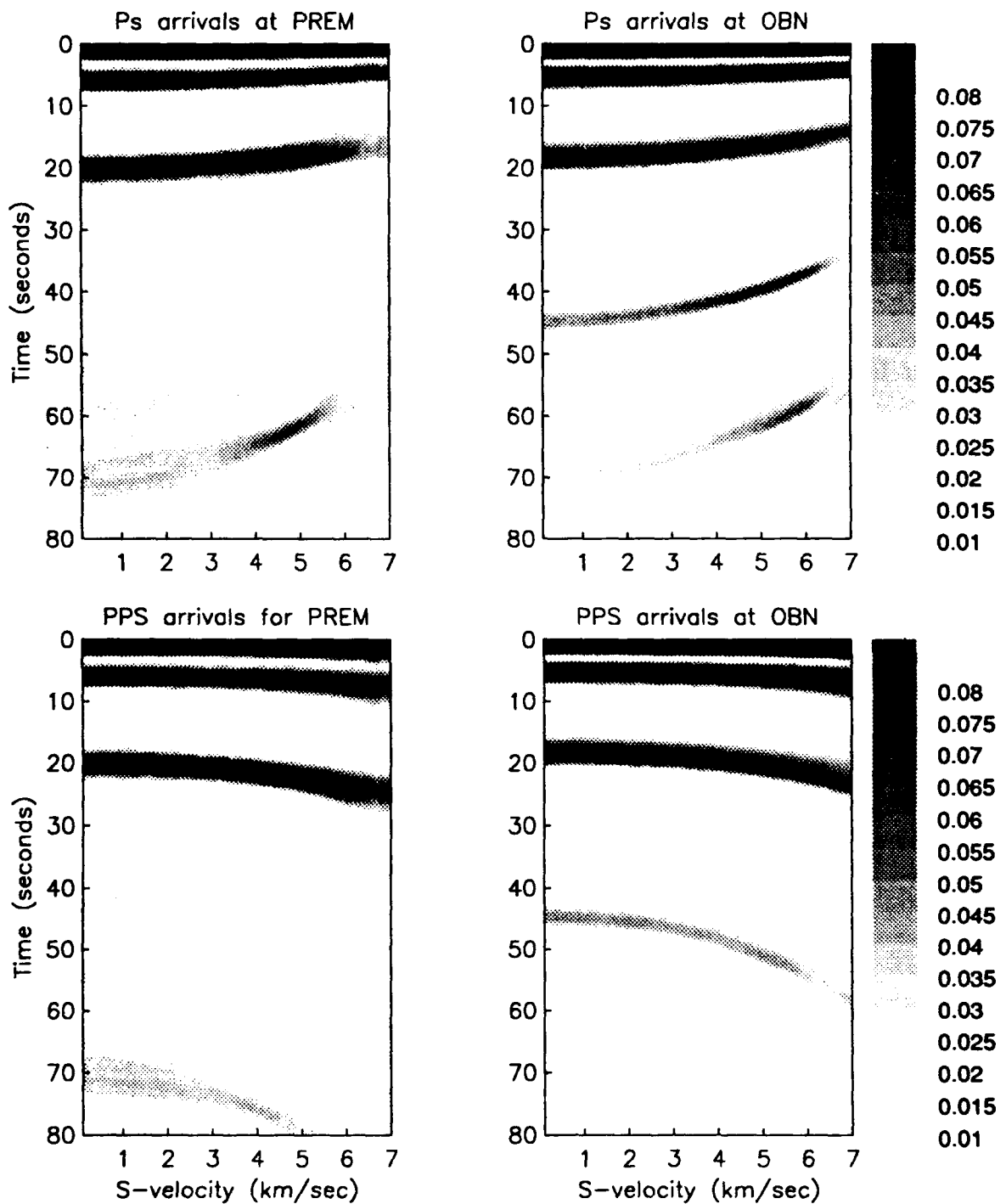


Figure 10. The two top velocity spectrum stacks are produced from the synthetics computed from PREM (left) and receiver functions computed from observed data recorded at Obninsk (right). The two lower plots are the corresponding P2p1s stacks.

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